Quantum Zeno Blockade for Next Generation Optical Switching in Fiber Systems

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I: Title Page

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II: Summary of Project

Introduction: All-optical switching is crucial for efficient optical communications. The quantum Zeno effect can be used to induce or inhibit optical switching through a variety of processes, all of which share the common characteristic that the evolution of one quantum state into another be inhibited or induced based on the presence or absence of a controllable and continuous quantum measurement. By utilizing this effect, it is the goal of this project to design and construct ultra-low power dissipation, ultra-low volume, fast all-optical switches. In particular, a fundamental limit in existing all-optical switching devices is due to the photon loss resulting from signal-pump coupling. When extended to the quantum domain, this photon loss additionally causes the quantum states of photonic signals to collapse (i.e., decohere). By using the quantum Zeno effect (QZE), it is possible to realize "interaction-free" switching that eliminates direct signal-pump coupling – i.e., QZE for all-optical switching.

The concept of "interaction-free" phenomenon was first proposed as "measurement without touching" and has recently been extended to quantum logic and counterfactual quantum computation. In our application to all-optical switching, we assume the signal wave is initially in state |0>. If uninterrupted, it will coherently evolve into an orthogonal state |1>. To induce switching, we apply a pump wave which couples |1> to an ancillary state |2>; this coupling disrupts the coherent evolution from |0> to |1> and the signal is frozen in |0>. Thus, the signal output is switched from |0> to |1> depending on the presence of the pump wave.

In this project, we explored QZE based all-optical applications via two approaches, exploiting second-order nonlinear effects in crystalline materials and third-order nonlinearities in Rb-immersed nano fibers, respectively.

Approach I: Our first implementation, a proof-of-principle, is to embed a $\chi^{(2)}$-nonlinear crystal in a Fabry-Perot cavity to observe interaction-free coupling of pump and signal waves. The cavity is designed to be resonant for both the signal and pump waves. In the absence of the pump, the signal wave applied from, say, the left, is resonantly coupled with the cavity mode. Eventually, it exits from the right end after a time delay. To induce switching, we apply a pump wave to the cavity, also through the left-end layer. In the cavity, the signal and pump waves undergo sum-frequency generation (SFG) (or difference-frequency generation). The SFG dynamics shifts the cavity out of resonance, resulting in the signal being reflected from the cavity. Note here that the SFG only "potentially" happens, as ideally the signal would never enter the cavity. Moreover, by applying the pump pulse slightly ahead of the signal pulse, the pump will pass through the cavity unaffected (as there is ideally no signal field in the cavity). This experiment verifies the interaction-free principle upon which our proposal is built. In addition, it will herald the key experimental parameters to implement the switch in a microresonator, which will lead to substantially smaller pump powers with almost no dissipation of pump energy.

Using a similar SFG process in a triply-resonant microresonator, the low inherent quantum-noise level in $\chi^{(2)}$ processes gives rise to substantially improved performance over existing logic-gate designs. Explicitly using lithium-niobate mircrodisks, we proposed interaction-free Fredkin gates, which are designed with telecom-band applications in mind. For these logic gates, the threshold pump peak power to achieve a gate contrast >100 and a signal loss <10% is hundreds of microwatts for practical parameters of the devices. Based on this analysis, the experimental realization of a triply-resonant LN microdisk will lead to an all-optical switch with very low threshold pump powers and virtually no dissipation of pump energies, i.e., they have fan-in/fan-out capabilities.

Significance of Approach I: Strong optical nonlinearities have been the foundation of many applications in classical and quantum optics. Recently, the burgeoning field of high Q nonlinear micro- and nano-cavities has emerged as a new chip-scalable platform for photonic information processing, which requires only modest (< 1fJ) energies and can be nearly lossless. In addition, by utilizing the quantum Zeno effect, interaction-free operations can be implemented, which eliminate the otherwise inevitable energy dissipation and background scattering processes. A pursuit towards low-light level optical interactions, hence, can simultaneously address fundamental and practical problems faced by both classical and quantum information processing. In fact, by analyzing a $\chi^{(2)}$-nonlinear Lithium Niobate (LN) microresonator, it has been shown that strong, noise-free interaction can be realized among single photons, thereby uncovering pathways to unprecedented applications such as optical transistors and deterministic quantum logic gates. Such a realization has an inherent advantage over resonant optical interactions with matter systems due to its compact experimental setup and a room-temperature operation.

We have proposed an interaction-free scheme for all-optical switching which does not rely on the physical coupling between signal and control waves. The interaction-free nature of the scheme allows it to overcome the fundamental photon-loss limit imposed by the signal-pump coupling. The same phenomenon protects photonic-signal states from decoherence, making devices based on this scheme suitable for quantum applications.

We have experimentally realized such an interaction-free coupling in both the Fabry-Perot proof-of-concept and the microresonator implementations. Our proof-of-concept experiment highlighted the many different regimes of operation for an interaction-free switch, and showed that in the optimal case of a “coherent”-loss mechanism mediating the Zeno effect, high-contrast switching is possible with substantially smaller powers than in the incoherent (or irreversible) case. In addition, it showed the simplicity of our scheme – without requiring any resonant matter-light interactions, we could in principle achieve few-photon level switching at room-temperature in a scalable architecture.

In our micro-resonator experiment, we were able to demonstrate, for the first time, strongly non-degenerate three-wave mixing with high conversion efficiencies. By developing the theoretical aspects for finding the phase-matching, we can now alter the parameters of the disk and find the phase-matching temperature without much trial-and-error methods. In addition, considerably smaller microdisks were fabricated without any loss in the intrinsic *Q* of the resonators, which will enable exotic applications such as deterministic quantum logic in this architecture. We have developed the theoretical model for the latter using feasible parameters for the microresonator which will pave the way towards deterministic entanglement of two independent photons and high-fidelity quantum C-NOT gates as well.

Approach II: On another track, we explored the feasibility of using tapered nano-fiber (TNF) embedded in Rb vapor to realize ultra-low light level, high speed optical modulators and switches using QZE. A TNF produces an extremely small confinement of optical fields, with an effective mode area of 0.2 μm^2. The evanescent field of the TNF interacts with surrounding Rb atoms, which exhibit very strong non-linearity near an optical dipole transition. The combination of these two effects hold the promise of realizing many different forms of non-linear optical effects at a very low light level, including QZE based modulators and switches.

Specifically, we fabricated TNFs using the conventional heating and pulling process. While the fiber is being pulled, the transmission through the fiber is monitored with a photo-detector. In addition, a camera is used to view the tapered section. Once the fiber becomes thinner than 1 μm in diameter, the fiber develops a bluish tinge. We made a set of fibers corresponding different color patterns. The diameters of these fibers were then measured with an SEM, and a look-up table was developed. Later, this lookup table was used to decide when to stop the pulling process for a given desired fiber diameter. For most of the experiments, we used a TNF with a diameter of about 400 nm, which was deemed to be optimal via numerical simulations.

The TNF was then mounted on a custom-made chuck, and loaded into a Rb vapor cell, using a Teflon feed-through. The chuck was heated to about 100 degree Celsius in order to prevent Rb from sticking to the fiber. The vapor cell was connected to an oven which contained solid Rb, which, when heated, produced the Rb vapor. As an alternative approach, we also used Rb getters in order to produce the Rb vapor, by passing a controlled current through the getters.

For realizing QZE effect based switches and modulators, we made use of Zeeman sublevel transitions within the D1 as well as the D2 manifolds of ^{87}Rb. In one experiment, we used a V-type transition to demonstrate an optical modulator with very low (~40 nW) of pump power, employing QZE. The findings of this experiment are summarized in figure 1. More information about these and related TNF experiments are presented later in this report, as well as in the enclosed papers and preprints.

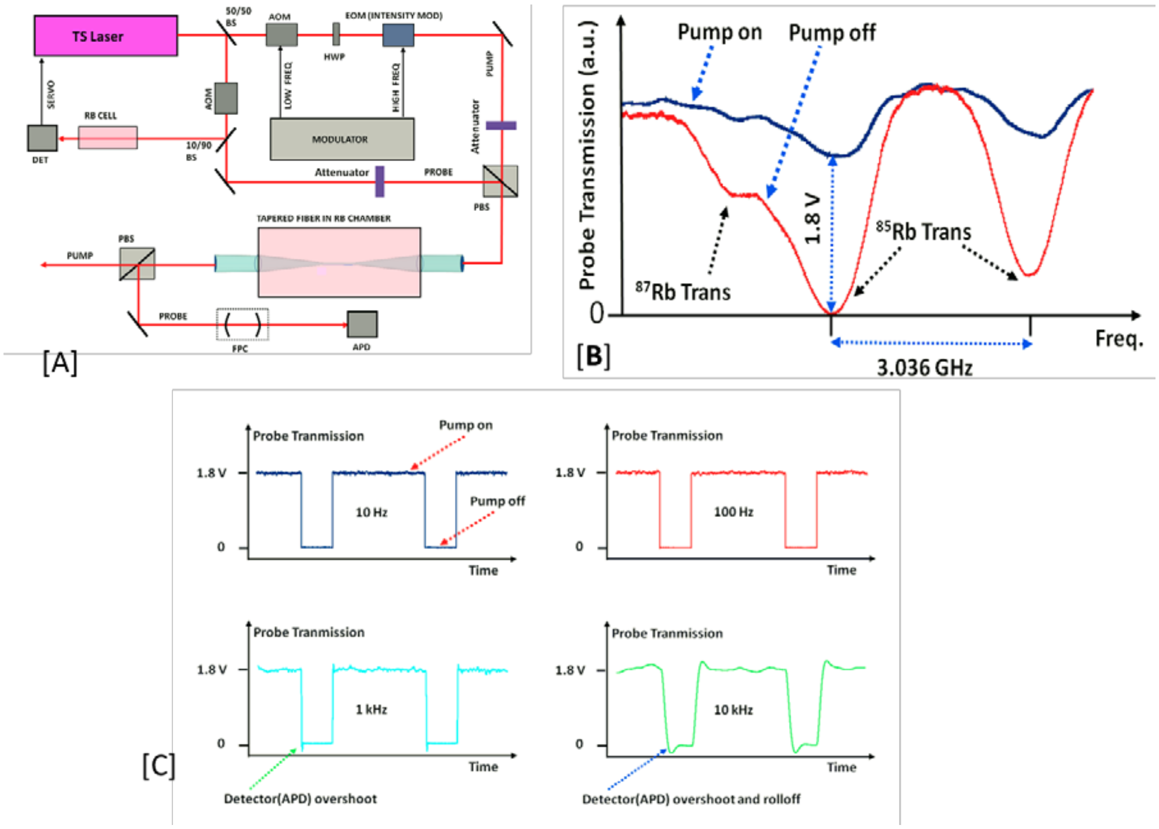

Figure 1: (a) Experimental setup for demonstrating a V-system QZE modulator, (b) Probe transmission spectrum with pump turned on and turned off, (c) Near 100% modulation depth observed for the probe.

In addition to using the TNF, we carried out a set of proof-of-principle experiments using ladder transitions in a conventional, heated Rb vapor cell. First, we demonstrated an all-optical modulator using the $5S_{1/2} – 5P_{1/2} – 6S_{1/2}$ ladder transition, where the control beam was at 795 nm, and the signal beam was at 1320 nm. The experimental result was in excellent agreement with theoretical simulations. In particular, we determined that the speed of such a modulator is limited by the spontaneous decay rate (about 5 MHz) of the intermediate state. We then developed a scheme for circumventing this limit, by using a high pressure buffer gas to enhance significantly this decay rate. Our simulations show that modulation at speeds approaching 100 GHZ or higher should be possible using this approach. If realized in a TNF, this would lead to an unprecedented combination of high-speed and low-power optical modulation. Work is currently in progress to demonstrate the high-speed modulation using an Ethane buffer gas loaded free-space Rb vapor cell.

Next, we carried out an experiment to demonstrate a QZE based optically-controlled high speed QZE based polarizer, using again the $5S_{1/2} – 5P_{1/2} – 6S_{1/2}$ ladder transition, where the control beam was at 795 nm, and the signal beam was at 1320 nm. We also carried out very extensive modeling, involving all the relevant Zeeman sublevels as well as velocity averaging, to simulate the behavior of this polarizer. The experimental result was found to be in excellent agreement with this model. If realized in TNF, this would lead to a very low-power, high-speed optically controlled polarizer. When realized using the free space vapor cell, it is also expected to be very useful for high-speed Stokesmetric imaging.

In a parallel experiment, we used the same transitions to demonstrate an optically-controlled high speed QZE based waveplate. Again, we carried out very extensive modeling, involving all the relevant Zeeman sublevels as well as velocity averaging, to simulate the behavior of this waveplate, and the experimental result was found to be in excellent agreement with this model. If realized in TNF, this would lead to a very low-power, high-speed optically controlled waveplate. When realized using the free space vapor cell, it is also expected to be very useful for high-speed Stokesmetric imaging.

The next step in this process would be to combine the polarizer and waveplate effect simultaneously, in a TNF, in order to realize an ultra-low light level, high speed QZE switch. We have also shown that this combination leads to optical logic gates, with potential application to digital signal processing in the optical domain, with very low levels of light.

A key problem we faced is that once in a while a Rb atom sticks to the TNF, leading to irreversible loss of transmission. We tried many different approaches to eliminate this problem, without much success. The final approach we are investigating is the use of a CO2 laser to heat the TNF in-situ. This work required a significant modification of our apparatus, and is still in progress.

Finally, in order to carry out the modeling of the very complex system involving many Zeeman sublevels, we have developed a new technique for solving the density matrix equations of motion involving an arbitrarily large number of energy levels. This algorithm is now being adopted by many groups in modeling the behavior of systems involving very large number of energy levels.

Significance of Approach II: A TNF produces an extremely small confinement of optical fields, with an effective mode area of 0.2 μm^2. The evanescent field of the TNF interacts with surrounding Rb atoms, which exhibit very strong non-linearity near an optical dipole transition. The combination of these two effects hold the promise of realizing many different forms of non-linear optical effects at a very low light level, including QZE based modulators and switches. Specifically, we have also identified

- A novel technique for making a very high speed all-optical modulator
- A novel technique for realizing a high-speed, ultra-low light level all optical switch using a combination of optically controlled polarization rotation and waveplate effects
- A novel type of ultra-low light level optical logic gates
- A new approach for ultra-fast Stokesmetric imaging using free-space, high-speed optically controlled polarizers and waveplates

III. List of Significant Accomplishments

✓ **Performed systematic studies of all-optical switching based on quantum Zeno effect**
  - Discovered two characteristic regimes of operation: coherent and incoherent
  - Identified the conditions for achieving optimal switching performed

✓ **Proposed and analyzed two realizations of $\chi^{(2)}$ –based Zeno Switch**
  - Proof-of-concept Fabry-Perot Zeno switch (experimentally demonstrated)
  - Zeno switch using lithium-niobate microdisk (switching observed) and GaAs microdisk
  - Explored potentials of such switches for quantum applications

✓ **Devised Zeno-based methodology for deterministic generation of entanglement**
  - Employed Zeno effect to suppress the stochasticity inherent with photon scattering in nonlinear optical system
  - Explored other opportunities in quantum optical processing enabled by quantum Zeno effect

✓ **Demonstrated and systematically studied for the first time a quantum switch**
  - Achieved high speed (>100 GHz), low loss (~ 1dB), and no detectable in-band noise

✓ **Demonstrated $\chi^{(2)}$ –based Zeno Switching with high contrast (35:1)**
  - Tested Zeno switching systematically in the coherent and incoherent regimes.
  - Experimental results agree with theory without use of any fitting parameter

✓ **Demonstrated microdisk Zeno switching**
  - Achieved sum-frequency phase matching at a predicted temperature
  - Achieved over 60% contrast probe switching with under 60 mW in-coupled control power and 80% with under 200 mW power.
  - Demonstrated pulsed operation of our switch

- ✓ Demonstrated QZE based all-optical cross-modulation, with ~40 nW of pump power, using a tapered nano-fiber embedded in a Rb vapor cell, with ~100% modulation depth [Optics Express, Vol. 19, No. 23, 22874 (2011)]

- ✓ Demonstrated QZE based all-optical cross modulation at telecom wavelength at a speed of up to 7 MHz, using a ladder transition in Rb vapor, with ~100% modulation depth [Optics Express 13798, Vol. 20, No. 13, 18 June (2012)]

- ✓ Developed a technique for telecom wavelength, QZE based all-optical modulation at a speed of as high as 100 GHz, using a high-pressure buffer gas loaded Rb vapor cell, and employing a 4-level ladder transition. [Optics Express 13798, Vol. 20, No. 13, 18 June (2012)]

- ✓ Demonstrated optically controlled polarizer for a QZE based all optical switch at telecom wavelength, using a ladder transition [paper submitted for publication]

- ✓ Demonstrated optically controlled waveplate for a QZE based all optical switch at telecom wavelength, using a ladder transition [paper submitted for publication]

- ✓ Developed a generalized code for modeling an atomic system with arbitrarily large number of levels, and employed it for modeling all the experiments described above, including all the hyperfine and Zeeman sublevels [paper submitted for publication]

- ✓ Shown how free space versions of Rb-ladder-transition based optically controlled polarizers and waveplates can be used to perform very high speed Stokesmetric imaging.

- ✓ Shown how a combination of the optically controlled polarizer and waveplate effects can be used to realize all-optical logic gates.

IV. Account of Progress by Task

IV. A: Fiber testbed for Zeno-based Switching

<u>Objective:</u> Using the recently developed optical fiber-based ultrafast quantum switch, the objective is to test the observation of an optical analog of the quantum Zeno effect. In particular, a series of alternating polarizers and waveplates would serve as frequent measurements of a wave's polarization, which without the polarizers, would evolve adiabatically from |H> to |V>. With the polarizers in place, this evolution is inhibited due to the quantum Zeno effect.

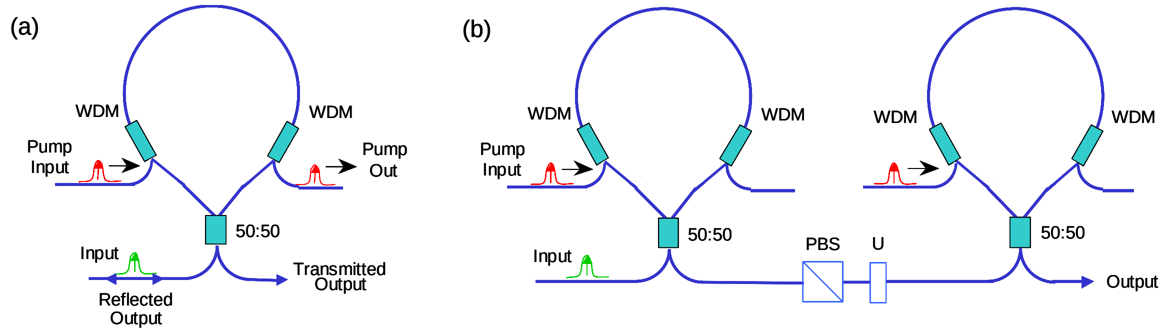

Fig. 2 (a) A controllable Sagnac loop. Using all-optical control beams, it can be set to switch between a totally reflective and a totally transmissive mode. (b) Experimental plan for a fiber-based testbed with which to study Zeno-based optical switches. Using a controllable cavity, periodic rotation and measurement cycles can be optically controlled.

Accomplishment: The fiber-based testbed uses a controllable cavity, periodic rotation, and measurement cycles to observe and characterize Zeno-based Switching. Figure 2 details an experimentally realizable version of the Zeno-based switching model. By using custom-designed, optically controllable Sagnac reflectors, we can create a fiber-cavity where input pulses can be switched in, stored for an arbitrary number of cycles, and switched out. The number of cycles over which the pulses can be stored is set by the angle of the wave-plate (U) after the polarization beamsplitter (PBS). Thus the 'measurement-strength' parameter R_V becomes controllable and can be used as a knob to study the core physics behind the Zeno-based switching. For this experiment, we developed a self-referential quantum process tomography to faithfully measure and compensate the fiber-induced unitary rotations on the signal's polarization. In addition, we were able to utilize the switch as a cavity and a selectable-delay to observe the Zeno-type effects in the testbed.

Conclusion and Remarks: We developed and utilized a self-referential quantum process tomography method to observe the Zeno effect in optical fiber using the ultrafast all-optical switch to create a cavity and use it as a selectable delay.

IV. B: Zeno-based All-optical Switching in Nonlinear Waveguides

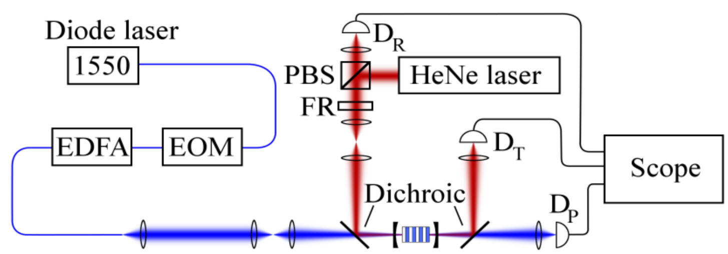

Figure 3. Experimental setup. EDFA: Erbium-Doped Fiber Amplifier. EOM: Electro-Optic Modulator. PBS: Polarizing beam-splitter. FR: Faraday Rotator.

Objective: The purpose of the free-space test bed was to investigate the fundamental operation of our switching approach in an environment that was more easily tuned and controlled compared to a microdisk approach. Specifically, we wanted to demonstrate switching, and compare the performance of the system with the theoretically-predicted performance, as well as investigate several different regimes of the switch (i.e., doubly resonant, slightly off resonant, and singly resonant).

Accomplishments: We have developed the theory of all-optical switching using quantum Zeno effect in nonlinear optical systems. Our studies revealed two characteristic operational regimes, namely coherent and incoherent Zeno regime, realized through coherently and dissipatively coupling the switched signal to external degrees of freedom by the pump, respectively. While both can lead to nearly noiseless switching, we found that the coherent Zeno switching is much more pump-power efficient. This is in contrast to the widely-held belief that quantum Zeno effect requires strong dissipation. In order to test our theory, we assembled the free-space optical setup as depicted in Fig. 3. We were successfully able to observe switching, showing a contrast of 35:1 (see Fig. 4), with the measured behavior accurately predicted with a theoretical model free of any fitting parameters. In addition to the doubly resonant case, we also observed switching in the singly-resonant case by introducing a dichroic mirror into the cavity, and investigated the behavior when slightly off resonant. In both cases, the measured response agreed with that predicted by our model.

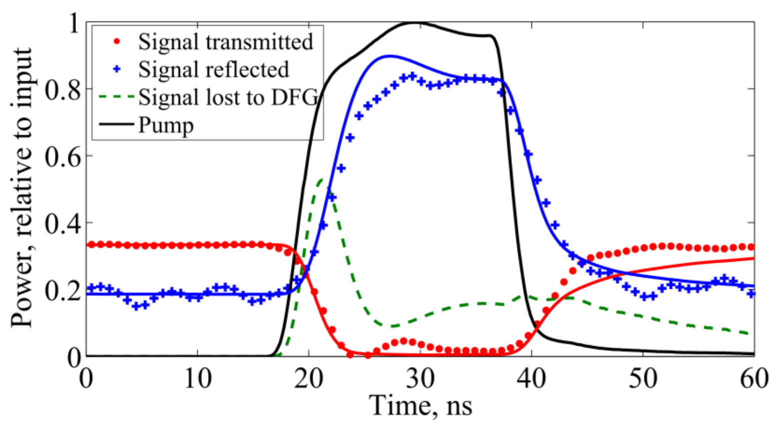

Figure 4. Switching results. When the pump is turned on, the transmitted signal drops nearly to zero, while the reflected signal increases. Very little light is ever created at the difference frequency. The solid lines for the transmitted and reflected light are not fits, but theoretical predictions based on the measured parameters of the cavity and pump.

Conclusion and Remarks: The free-space Zeno switching experiment was successful. We observed high-contrast switching based on the quantum Zeno effect for the first time, and verified that our model would accurately describe the experimental behavior. We are now able to apply this information towards triply-resonant, smaller mode volume systems such as the microdisk, in order to dramatically reduce the required pump power.

IV. C: Low Power Threshold Zeno Switching in Nonlinear Microcavities

Objective: The objective is to utilize the quantum Zeno effect mediated by the sum-frequency generation process in a triply resonant micro-resonator to implement an "interaction-free", ultralow-dissipation all-optical switch at low pump energies. To achieve this, theoretical modeling of the nonlinear dynamics of three interacting waves in a $\chi^{(2)}$ Lithium Niobate whispering-gallery-mode resonator (WGMR) has to be performed. Additionally, the selection rules in a spherically-symmetric WGMR have to be understood and applied to determine the modes yielding the maximal spatial overlap and hence maximum conversion efficiency. The phase matching temperature at which the frequencies of these modes add up has to be determined theoretically and found experimentally. The LN microresonator and the supporting structure, providing optical and electrical coupling along with tight temperature stabilization, needs to be fabricated, assembled and tested.

Accomplishments: We have manufactured a MgO-doped Lithium Niobate z-cut microdisk (R ~ 0.6mm) and evanescently coupled it to a diamond prism. Diamond-polishing was used to obtain absorption-limited Q > 2×10^7 and Q > 4×10^7 for the signal (780nm) and pump (1560nm) waves, respectively. We observed, for the first time, strongly non-degenerate naturally phase-matched sum-frequency generation (SFG) in this

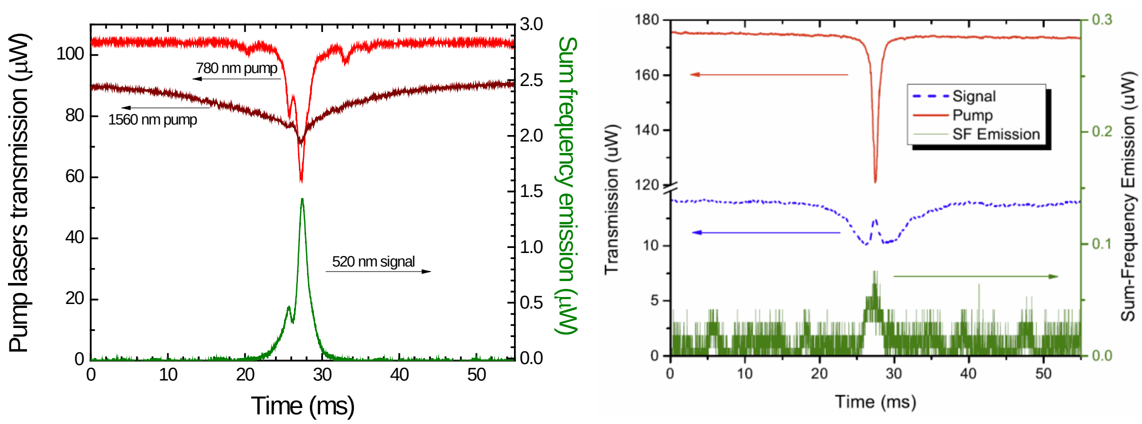

Figure 5. Strongly (left) and weakly (right) pumped SFG in a triply-resonant WGMR. In the weakly-pumped case Zeno-based mode splitting is evident.

WGMR between the pump and the signal, as shown in Fig. 5. Even at this stage the signal mode splitting indicative of the quantum Zeno effect was evident.

Furthermore, we have demonstrated quantum Zeno switching, when a stronger pump pulses modulated the weaker CW signal, as shown in Fig. 6. We observed this modulation at extremely low pump energy of tens of pJ. Remarkably, the SFG output was reduced when the pump power was increased. At higher pump powers, an additional nonlinear loss for the signal wave is created due to its upconversion, leading to the reduction of its internal Q-factor and the coupling contrast. As a result, a smaller portion of the signal wave enters the resonator and the SFG efficiency is reduced. This behavior is a manifestation of the “coherent" quantum Zeno effect for the signal wave, where the “potential" for the upconversion decouples the signal field from the cavity.

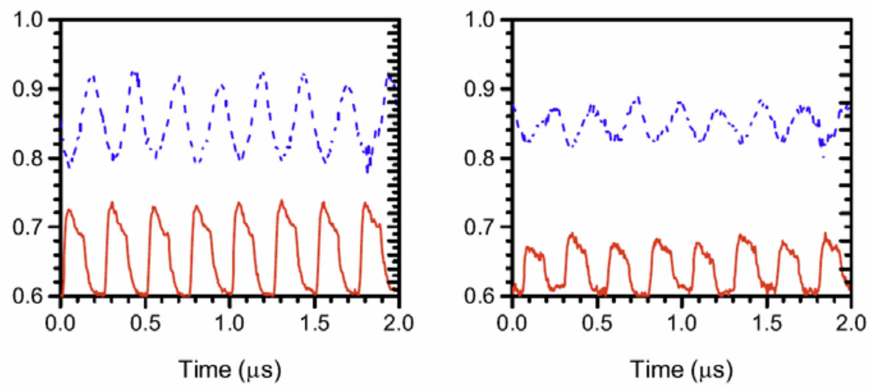

Figure 6. Zeno-based modulation of the initially-CW signal (dashed line) by pulsed pump (solid line) in a WGMR. The pump pulse energies are 34 pJ (left) and 8 pJ (right).

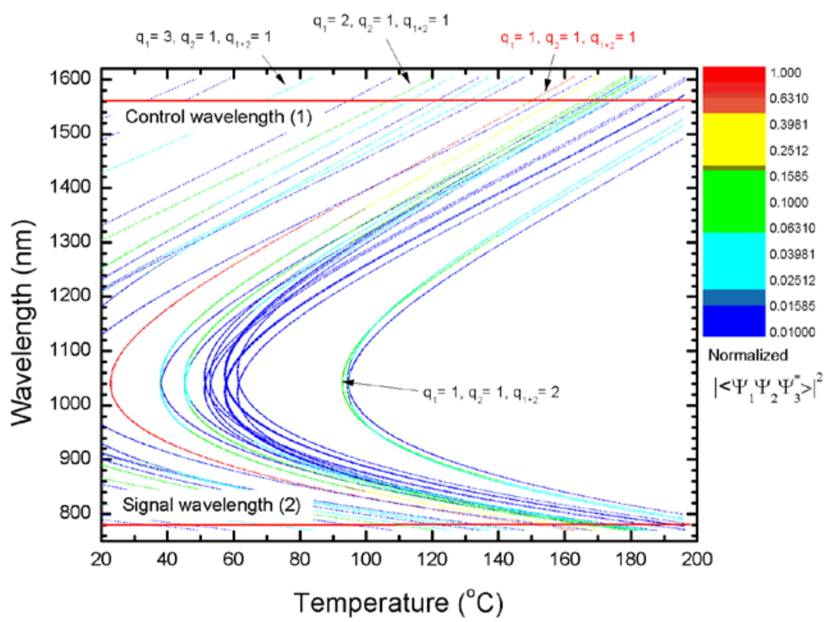

Figure 7. Tuning curves (the pump and signal temperature dependence) for different SFG channels in our WGMR. Color represents the conversion efficiency. Achieving the optimal nonlinear interaction has required a careful theoretical modeling

To optimize the three-wave overlap inside the resonator and to estimate the phase matching temperature, we have developed specialized software. It has been discovered that many triply resonant phase matching channels may exist in a spherically symmetric WGMR, each yielding different interaction efficiency and requiring special phase matching temperature, as shown in Fig. 7. However the most efficient channel is the one that couples the fundamental modes. Achieving a triple resonance for a selected channel requires tuning of each WGM's frequency such that the energy conservation is fulfilled to better than a WGM linewidth. This has been achieved for ordinary pump and signal and extraordinary sum-frequency WGMs due to different temperature dependencies of the ordinary and extraordinary refraction indices.

Conclusion: We utilized sum-frequency generation (SFG) in a high-Q lithium niobate whispering gallery mode (WGM) microresonator as a “coherent" loss mechanism to observe the quantum Zeno blockade which manifests itself as the control pulse preventing the probe pulse from entering the resonator. We further demonstrate the “interaction-free" coupling of two optical fields, which in our system means the suppressed SFG, and study the temporal dynamics of the coherent quantum Zeno effect to observe modulation of the probe induced by the pump. This study has shown that we need to fabricate a much smaller microdisk to ensure a further reduction in pump power thresholds aiming towards single-photon operations, and alter the morphology of the resonator to ensure single-mode operation at each of the three wavelengths to further increase the interaction between the modes. Based on the experience gained during this effort, we believe that both requirements are feasible.

IV. C: Zeno Switching using Nano-fiber embedded in Rb Vapor

Objective: On this track, we explored the feasibility of using tapered nano-fiber (TNF) embedded in Rb vapor to realize ultra-low light level, high speed optical modulators and switches using the quantum Zeno effect (QZE). A TNF produces an extremely small confinement of optical fields, with an effective mode area of 0.2 μm^2. The evanescent field of the TNF interacts with surrounding Rb atoms, which exhibit very strong non-linearity near an optical dipole transition. The combination of these two effects hold the promise of realizing many different forms of non-linear optical effects at a very low light level, including QZE based modulators and switches.

Accomplishments: For realizing QZE effect based switches and modulators, we made use of Zeeman sublevel transitions within the D1 as well as the D2 manifolds of ^{87}Rb. In one experiment, we used a V-type transition to demonstrate an optical modulator with very low (~40 nW) of pump power, employing QZE. More information about these and related TNF experiments are presented later in this report, as well as in the enclosed papers and preprints.

In addition to using the TNF, we carried out a set of proof-of-principle experiments using ladder transitions in a conventional, heated Rb vapor cell. First, we demonstrated an all-optical modulator using the $5S_{1/2} – 5P_{1/2} – 6S_{1/2}$ ladder transition, where the control beam was at 795 nm, and the signal beam was at 1320 nm. The experimental result was in excellent agreement with theoretical simulations. In particular, we determined that the speed of such a modulator is limited by the spontaneous decay rate (about 5 MHz) of the intermediate state. We then developed a scheme for circumventing this limit, by using a high pressure buffer gas to enhance significantly this decay rate. Our simulations show that modulation at speeds approaching 100 GHZ or higher should be possible using this approach. If realized in a TNF, this would lead to an unprecedented combination of high-speed and low-power optical modulation. Work is currently in progress to demonstrate the high-speed modulation using an Ethane buffer gas loaded free-space Rb vapor cell.

Next, we carried out an experiment to demonstrate a QZE based optically-controlled high speed QZE based polarizer, using again the $5S_{1/2} – 5P_{1/2} – 6S_{1/2}$ ladder transition, where the control beam was at 795 nm, and the signal beam was at 1320 nm. We also carried out very extensive modeling, involving all the relevant Zeeman sublevels as well as velocity averaging, to simulate the behavior of this polarizer. The experimental result was found to be in excellent agreement with this model. If realized in TNF, this would lead to a very low-power, high-speed optically controlled polarizer. When realized using the free space vapor cell, it is also expected to be very useful for high-speed Stokesmetric imaging.

In a parallel experiment, we used the same transitions to demonstrate an optically-controlled high speed QZE based waveplate. Again, we carried out very extensive modeling, involving all the relevant Zeeman sublevels as well as velocity averaging, to simulate the behavior of this waveplate, and the experimental result was found to be in excellent agreement with this model. If realized in TNF, this would lead to a very low-power, high-speed optically controlled waveplate. When realized using the free space vapor cell, it is also expected to be very useful for high-speed Stokesmetric imaging.

The next step in this process would be to combine the polarizer and waveplate effect simultaneously, in a TNF, in order to realize an ultra-low light level, high speed QZE switch. We have also shown that this combination leads to optical logic gates, with potential application to digital signal processing in the optical domain, with very low levels of light.

A key problem we faced is that once in a while a Rb atom sticks to the TNF, leading to irreversible loss of transmission. We tried many different approaches to eliminate this problem, without much success. The final approach we are investigating is the use of a CO2 laser to heat the TNF in-situ. This work required a significant modification of our apparatus, and is still in progress.

Finally, in order to carry out the modeling of the very complex system involving many Zeeman sublevels, we have developed a new technique for solving the density matrix equations of motion involving an arbitrarily large number of energy levels. This algorithm is now being adopted by many groups in modeling the behavior of systems involving very large number of energy levels.

<u>Conclusion:</u> The work carried out has paved the way for further investigations on different fronts, for many different applications. In addition, some challenges remain to be overcome. These are listed below:

- Carry out an experiment in a buffer-gas loaded vapor cell to demonstrate all-optical modulation at a speed of ~100 GHz, using a ladder transition in Rb.

- Demonstrate the combination of optically controlled polarizer and waveplate for realizing an ultra-low light level, high speed all optical QZE switch

- Demonstrate optical logic gates using a combination of optically controlled polarizer and waveplate

- Demonstrate high-speed Stokesmetric imaging by using free-space optically controlled polarizer and waveplate using a ladder transition in Rb vapor

- Explore the use of a CO_2 laser for in-situ heating of a TNF, in order to circumvent the problem of loss of transmission due to deposition of Rb on the TNF.

V. Conclusion and Outlook

During the course of this project, we have made significant theoretical and experimental progress towards developing new all-optical technology based on the quantum Zeno effect. On the theory side, we have performed systematic studies of the quantum Zeno effect in a nonlinear optical environment, exploring different dynamical regimes and in multiple optical systems. Our theoretical findings highlight the perspective of interaction-free all-optical logic operations whereby all-optical phase, frequency, and path switching can be implemented without the need for the control and signal beams to overlap in the switching device at any significant level. As a result, the problem of photon loss arising from the signal-control coupling, which is inherent with existing all-optical devices, can be overcome. The same interaction-free feature also eliminates quantum decoherence and phase noise otherwise inevitable with devices of this kind, making our approach suitable for quantum applications. Applying this to room-temperature, scalable optical systems made of second-order nonlinear microresonators, we have found that a new class of all-optical switches can be realized with ultralow control power, nearly no loss or heat deposition, and high contrast. We have also shown how such devices can be improved to operate at the single-photon level, where deterministic quantum logic gates can be realized between photonic signals, thus providing a solution to a long outstanding quest in the broad field of quantum information processing.

On the experimental side, we have performed a series of experiments testing and demonstrating all-optical switching using the quantum Zeno effect. The first experiment, a proof-of-principle, used a $\chi^{(2)}$-nonlinear crystal in a Fabry-Perot cavity to observe interaction-free coupling of pump and signal waves. We successfully observed a high switching contrast of 35:1, and by changing experimental parameters, compared the switching performance in various regimes of the Zeno effect. All of our experimental results were predicted well by our theory without the use of any fitting parameter, confirming our understanding of Zeno-based switching. Based on the same principle but using a triply-resonant microresonator, we then proceeded to build interaction-free optical switches with low pump power (about tens of microwatts) and virtually no dissipation of pump energies, i.e., they have fan-in/fan-out capabilities. We were able to demonstrate, for the first time, strongly non-degenerate three-wave mixing with high conversion efficiencies. We then demonstrated quantum Zeno switching, in which stronger pump pulses modulated the weaker CW signal. We observed this modulation at extremely low pump energy of tens of pJ. Remarkably, the signal output was increased when the pump power was increased. At higher pump powers, an additional nonlinear loss for the signal wave is created due to its upconversion, leading to the reduction of its internal Q-factor and the coupling contrast. As a result, a smaller portion of the signal wave enters the resonator and the nonlinear coupling between the pump and signal is suppressed. This behavior is a manifestation of the “coherent" quantum Zeno effect for the signal wave, where the “potential" for the upconversion decouples the signal field from the cavity.

With the above theoretical and experimental developments, we are in an excellent position to carry on the studies of Zeno-based all-optical switching into new regimes in both the classical and quantum domains. In the classical domain, the goal is to build practical optical transistors with fan-in/fan-out capabilities, which are suitable for use as elementary blocks for large-scale all-optical information processing. The microdisk switch we demonstrated in this project can already fulfill a majority of requirements for this task, such as no heat deposition, low loss, logic level restoration, and so on. A challenge that remains to be addressed, however, is the speed of operation. Our current demonstration is in the low sub-GHz regime. In future applications, 100 GHz or higher speed will be desirable. For such, we need to operate the cavity in the very strong coupling regime while reducing the cavity volume further. We are currently working on better fabrication and operation platforms to this end. In the quantum domain, on the other hand, we aim at developing practical, room temperature, solid-state, chip-scale devices for implementing quantum logic operations among photonic signals in a deterministic manner. The lack of such deterministic quantum devices has become a bottleneck for developing large-scale quantum information processing systems. The microdisk device we developed during this proposal can potentially satisfy this goal. In fact, our recent simulations have discovered that noise-less controlled phase gate can be realized between single-photon quantum signals with >95% fidelity. It is the goal of our future studies to realize such a gate in lab.

Finally, the studies of Zeno effect in Rb-vapor embedded nano-fiber have paved the way for further investigations on different fronts, for many different applications. These include (a) demonstration of all-optical modulation at a speed of ~100 GHz, using a ladder transition in Rb, (b) demonstration of an ultra-low light level, high speed all optical QZE switch using a combination of optically controlled polarizer and waveplate in a TNF (c) demonstration of ultra-low light level, high speed optical logic gates using a combination of optically controlled polarizer and waveplate in a TNF, and (d) demonstration of high-speed Stokesmetric imaging by using free-space optically controlled polarizer and waveplate using a ladder transition in Rb vapor.

A significance challenge that remains to be overcome is the problem of loss of transmission in a TNF once a Rb atom sticks to it. We are exploring the use of a CO2 laser for in-situ heating of the TNF, in order to circumvent this problem.

VI. List of Publications and Presentations

List of Journal Publications and Preprints

1. Yu-Ping Huang, Joseph B. Altepeter, and Prem Kumar, "Interaction-free all-optical switching via the quantum Zeno effect," Phys. Rev. A 82, 063826 (2010).
2. Yu-Ping Huang and Prem Kumar, "Interaction-free all-optical switching in $\chi^{(2)}$ microdisks for quantum applications," Opt. Lett., 35, 2376 (2010).
3. Yu-Ping Huang, Joseph B. Altepeter, and Prem Kumar, "Heralding single photons without spectral factorability," Phys. Rev. A 82, 043826 (2010).
4. Yu-Ping Huang, Joseph B. Altepeter, and Prem Kumar, "Optimized heralding schemes for single photons," Phys. Rev. A 84, 033844 (2011).
5. Kahraman G. Köprülü, Yu-Ping Huang, and Prem Kumar, "Lossless shaping of single photons," Opt. Lett. 36, 1674 (2011).
6. Matthew A. Hall, Joseph B. Altepeter, and Prem Kumar, "Ultrafast Switching of Photonic Entanglement", Phys. Rev. Lett. 106, 053901 (2011).
7. Matthew A Hall, Joseph B Altepeter and Prem Kumar, "All-optical switching of photonic entanglement," New J. Phys. 13, 105004 (2011).
8. Monika Patel, Joseph B. Altepeter, Yu-Ping Huang, Neal N. Oza, and Prem Kumar, "Erasing quantum distinguishability via single-mode filtering," Phys. Rev. A 86, 069903 (2012).
9. Yu-Ping Huang, and Prem Kumar, "Interaction-free quantum optical fredkin gates in $\chi^{(2)}$ microdisks," IEEE Journal of Selected Topics in Quantum Electronics 18, 600 (2012);
10. Yu-Ping Huang and Prem Kumar, "Antibunched Emission of Photon Pairs via Quantum Zeno Blockade," Phys. Rev. Lett. 108, 030502 (2012).
11. Yu-Ping Huang and Prem Kumar, "Quantum Theory of All-Optical Switching in Nonlinear Sagnac Interferometers," New J. Phys. 14, 053038 (2012).
12. Jonathon Hu, Yu-Ping Huang, and Prem Kumar, "Self-stabilized Quantum Optical Fredkin Gate," Optics Letters 38, 522 (2013).
13. Yu-Zhu Sun, Yu-Ping Huang, and Prem Kumar, "Photonic Nonlinearities via Quantum Zeno Blockade," Phys. Rev. Lett. 110, 223901 (2013)
14. Yu-Ping Huang, Vesselin Velev, and Prem Kumar, "Quantum frequency conversion in nonlinear microcavities," Opt. Lett. 38, 2119 (2013).
15. Yu-Ping Huang and Prem Kumar, "Mode-resolved photon counting via cascaded quantum frequency conversion," Opt. Lett. 38, 468 (2013).
16. Kevin T. McCusker, Yu-Ping Huang, Abijith Kowligy, and Prem Kumar, "Experimental demonstration of interaction-free all-optical switching via the quantum Zeno effect", Phys. Rev. Lett. 110, 240403 (2013).

17. Dmitry V. Strekalov, Abijith S. Kowligy, Yu-Ping Huang, and Prem Kumar, “Optical sum-frequency generation in whispering gallery mode resonators,” submitted to Phys. Rev. Lett., arXiv:1304.4217
18. Dmitry V. Strekalov, Abijith S. Kowligy, Yu-Ping Huang, and Prem Kumar, “Observation of Quantum Zeno Blockade in microresonators,” (in preparation – to be submitted to Phys. Rev. Lett.)K. Salit, M. Salit, K. Subramanian, Y. Wang, P. Kumar, and M.S. Shahriar,. “Ultra-Low Power, Zeno Effect Based Optical Modulation in a Degenerate V-System with a Tapered Nanofiber in Atomic Vapor,” Optics Express, Vol. 19, No. 23, 22874 (2011)
19. S. Krishnamurthy, Y. Wang, Y. Tu, S. Tseng, and M.S. Shahriar, “High efficiency optical modulation at a telecom wavelength using the quantum Zeno effect in a ladder transition in Rb atoms,” Optics Express 13798, Vol. 20, No. 13, 18 June (2012).
20. Y. Wang, Y. Tu, S. Tseng, and M.S. Shahriar, “Optically controlled polarizer using a ladder transition for high speed Stokesmetric Imaging and Quantum Zeno Effect based optical logic,” Subramanian Krishnamurthy, submitted to Optics Express (2013)
21. Y. Wang, S. Tseng, Y. Tu, and M.S. Shahriar, “Optically controlled waveplate at a telecom wavelength using a ladder transition in Rb atoms for all-optical switching via the quantum Zeno effect,” Subramanian Krishnamurthy, submitted to Optics Express (2013)
22. M.S. Shahriar , Ye Wang, S.Krishnamurthy, Y. Tu, G.S. Pati, and S. Tseng, “Evolution of an N-level system via automated vectorization of the Liouville equations and application to optically controlled polarization rotation,” submitted to Journal of Modern Optics (2013).

List of Public Presentations, with indicators for any DOD or DARPA presentations

1. Yu-Ping Huang, Abijith S. Kowligy, Joseph B. Altepeter, and Prem Kumar, “Interaction-Free All-Optical Switching via Quantum Zeno Blockade,” Frontiers in Optics, FThS2, 2011
2. Dmitry V. Strekalov, Abijith S. Kowligy, Yu-Ping Huang, and Prem Kumar, “Observation of the quantum Zeno blockade in a $\chi^{(2)}$ microresonator,” CLEO 2013, San Jose, CA
3. Kevin T. McCusker, Yu-Ping Huang, Abijith S. Kowligy, Prem Kumar, *Experimental Demonstration of All-Optical Switching Using the Quantum Zeno Effect* presented at CQO X – QIM 2 conference, Rochester, NY (2013).

4. “Buffer-Gas Assisted High Speed Optical Modulator using Ladder Transitions in Rb,” Subramanian Krishnamurthy, Y. Wang, Y. Tu, S. Tseng, and M.S. Shahriar, OSA Annual Meeting, Orlando, FL, October 2013.
5. “All-Optical Switch at Telecom Wavelength based on the Quantum Zeno Effect (QZE),” Subramanian Krishnamurthy, Ye Wang, Yanfei Tu, Shih Tseng; Selim M. Shahriar, Conference on Lasers and Electro-Optics, San Jose, CA, June 2013.
6. “Optically controlled polarizer and waveplate at telecom wavelength for Quantum Zeno Effect based all-optical switch,” S. Krishnamurthy, Y. Wang, Y. Tu, S. Tseng and M.S. Shahriar, APS DAMOP conference in Quebec City, Canada, June 2013.
7. “Quantum Zeno effect based high speed optical modulator at a telecom wavelength in a ladder transition in Rb atoms,” K. Subramanian, Y. Wang, S. Tseng, Y. Tu, and M.S. Shahriar, presented at the OSA annual meeting, Rochester, NY (2012).
8. “Ultra-low Power Optical Modulation within Tapered Nano-fiber using 5S-5P-5D Ladder Transition of Rb Atoms,” Y. Wang, K. Subramanian, S. Tseng, Y. Tu, and M.S. Shahriar, presented at the OSA annual meeting, Rochester, NY (2012)
9. “Optically Controlled Waveplate at a Telecom Wavelength Using a Ladder Transition in Rb Atoms for All-Optical Switching via the Quantum Zeno Effect,” K. Subramanian, Y. Wang, S. Tseng, Y. Tu, and M.S. Shahriar, presented at the OSA annual meeting, San Jose, CA, Oct. 2011.
10. “High Efficieny, High Speed Optical Modulation at a Telecom Wavelength Using the Quantum Zeno Effect in a Ladder Transition in Rb Atoms,” K. Subramanian, Y. Wang, Y. Tu, S. Tseng, and M.S. Shahriar, presented at the OSA annual meeting, San Jose, CA, Oct. 2011
11. “High Bandwidth, Ultra-Low Power All Optical Modulation with a Nano-Fiber Embedded in Rb Vapor,” K. Salit, M. Salit, S. Krishnamurthy, Y. Wang, P. Kumar, and M.S. Shahriar, presented at the Conference on Lasers and Electro-Optics, San Jose, CA, May 2010.
12. “Atto-Joules, High Bandwidth All Optical Modulation with a Nano-Fiber Embedded in Alkali Vapor,” K. Salit, M. Salit, S. Krishnamurthy, Y. Wang, P. Kumar, and M.S. Shahriar, presented at OSA Annual Meeting, San Jose, CA, Oct. 2009.

List of Poster Presentations

1. Yu-Ping Huang and Prem Kumar, “Fredkin Gates in $\chi^{(2)}$ microdisks via Quantum Zeno Blockade”, Nonlinear Optics 2011
2. Abijith S. Kowligy, Yu-Ping Huang, and Prem Kumar, “All-Optical Switching in chi(2) microdisks via Quantum Zeno Blockade,” WE.Heraeus Foundation 492 Seminar on “Micro- and Macro-cavities for classical and non-classical light,” Bad Honnef, Germany (2011)
3. Kevin T. McCusker, YuPing Huang, Abijith S. Kowligy, Prem Kumar, *Experimental Demonstration of All-Optical Switching Using the Quantum Zeno Effect* presented at CQO X – QIM 2 conference, Rochester, NY (2013).